

# HIERARCHICAL CONTROL AND DRIVING

by

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## ABSTRACT

This dissertation begins with an overview of skilled performance and how hierarchical control theory (HCT) has been successful in explaining skilled performance. Next, two novel premises of HCT are generated that provide evidence for distinct, hierarchical control systems (outer and inner loops). These control systems have unique properties and lead to very different predictions when applied to complex skills. By manipulating primary task predictability and secondary task workload of a complex skill, these properties can be dissociated. This is followed by an application of HCT to driving and driver distraction. I discuss how secondary task cognitive workload affects driving performance and how previous research has not explained paradoxical patterns of driving performance (i.e., lane maintenance). Then two premises of HCT are generated and used to make predictions about lane maintenance. Next, another influential theory of skilled performance (ACT-R) is discussed, and this theory is contrasted with HCT in terms of predictions regarding lane maintenance. Two experiments are designed to test HCT and differentiate it from ACT-R. The results support the predictions of HCT and suggest that ACT-R is somewhat limited in its ability to fully explain lane maintenance. HCT provides a framework for future driving research as well as future research on a variety of complex skills.

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## INTRODUCTION

Complex skills are an essential part of human cognition and performance. Without complex skills, we would not be able to fly planes, conduct trains, or drive automobiles. When first performing a complex skill, performance is governed by controlled processes (Shiffrin & Schneider, 1977). This requires attention as a person monitors the novel/unpredictable situation in an attempt to perform successfully. Initially, this type of performance is effortful, slow, and relies on limited capacity attention (Strayer & Drews, 2007). With practice, certain complex tasks that initially required controlled processes can be performed with little effort or attention. At this point, performance is characterized as automatic, fast, and efficient. This transition happens when there is consistent mapping of stimulus and response over many trials (Shiffrin & Schneider, 1977). After further practice with consistent mapping, attention can be withdrawn from a task without major impairments in performance (Schneider & Fisk, 1982).

It is important to note the current research assumes that complex skills are goal directed (Logan & Crump, 2011). For example, musicians do not play instruments by accident, nor do drivers drive their cars by happenstance. Despite the fact that complex skills are goal directed, many times skilled performers do not know how they achieve high levels of performance (Tapp & Logan, 2011). To help account for this puzzling discrepancy, Fodor (1983) argued that there are separate control systems that bring about skilled performance. One system is similar to controlled processes and is easily brought into conscious awareness.

The other system is automatic and operates outside of awareness. This division was initially described in terms of a hierarchy with higher and lower levels of control. For example, Shaffer (1976) found that musicians often utilized two levels of control for musical performance. One level would monitor a song and notes to be played and another level would control the execution of finger movements. When a person first learns how to play the piano, the higher control level would be required for both processing the song and notes, as well as monitoring the hands to depress the proper keys. In these instances, the higher level is engaged and acting directly to achieve the task of playing the instrument, and performers are keenly aware of their performance. With practice, the higher level of control would not be needed to directly accomplish the task. Instead, some of the work would be offloaded to the lower level of control, which would then directly influence performance. Finally, with extensive practice, the lower control level can become encapsulated such that it does not necessarily require higher level processing. When this happens, performance on the task is characterized as automatic and requires minimal attention or effort unless the environment becomes unpredictable. If the environment becomes unpredictable, attention would be again required for successful performance on the task.

The notion of hierarchical control for skilled performance has advanced over the years and has been vetted using other tasks outside of musical performance. Recently, Logan and Crump (2009) used the metaphor of control loops rather than levels to describe complex typing and found that skilled typists rely on these outer and inner loops of control for their complex performance. Specifically, the outer loop of control was responsible for the words to be typed while the inner loop of control was responsible for the individual keystrokes. Interestingly, when participants allocated attention to their individual keystrokes,

performance declined. The authors explained this by claiming that the outer loop of control monitored the output of the inner loop, and this additional monitoring disrupted the encapsulated inner loop processing.

It is important to note that Logan and Crump's (2009) sample consisted of expert typists. Certainly, when first learning to type, attention must be allocated to what to type (i.e., thoughts or words on a screen), as well as how to type (i.e., finger movements). This suggests a high level of involvement from the outer loop of control, which is resource-demanding and effortful (Kahneman, 1973). With practice, typists can start to offload some of the work to the inner loop of control to accomplish the necessary keystrokes. Finally, with extensive practice, the task can be controlled directly by the inner loop, which is more automatic and requires minimal attention for efficient performance. What remains to be tested is how changes in the predictability of the testing environment would affect performance even for experts.

For expert performers, certain parameters of the environment must remain consistent and predictable for their performance to remain automatic and under the purview of the inner loop of control. One can imagine that an expert guitarist accustomed to playing one type of guitar will seem like a novice when switching to a different string instrument with very different characteristics. Likewise, if one were to exchange a traditional QWERTY keyboard (Noyes, 1983) for a DVORAK keyboard (Cassingham, 1986), typing would initially be a difficult, resource-demanding task. This would subsequently reactivate the outer loop of control for successful finger movements. In these examples, the novel configurations lead to an increase in the level of unpredictability of the testing environment. This uncertainty engages the outer loop of control to accomplish tasks that the inner loop of control had



previously been able to handle autonomously. Once again, this highlights the importance of consistent mapping in bringing about skilled performance in a predictable environment.

When the mapping is changed for a given task, performance becomes more similar to that of a novice (Shiffrin & Schneider, 1977). This is due to the increase in unpredictability of the environment, which subsequently requires attention to be allocated to the task. In addition to understanding complex skills in unpredictable testing environments, a hierarchical account of complex skill must accurately account for performance in highly predictable environments.

Interestingly, when the testing environment remains predictable but attention is nonetheless allocated to the task, complex skills can be disrupted. As previously mentioned, when expert typists pay attention to keystrokes, performance declines (Logan & Crump, 2009; Logan & Crump, 2011; Tapp & Logan, 2011). These disruptive effects have also been shown outside the realm of typing, suggesting that they are general characteristics of hierarchical control. For example, Beilock et al. (2002) had experienced golfers focus on swinging their clubs and experienced soccer players focus on kicking the ball and found that performance declined significantly compared to novices. Similarly, Gray (2004) had expert baseball players judge whether their bats were traveling up or down when a tone sounded. This allocation of attention to players' highly practiced skill disrupted batting performance. There have been similar findings with basketball free-throws (Hossner & Ehrlenspiel, 2010), hockey dribbling (Jackson, Ashford, & Norsworthy, 2006), and Frisbee throws (Ong, Bowcock, & Hodges, 2010), as well as in more traditional laboratory settings (Beilock & Carr, 2001; Hossner & Ehrlenspiel, 2010). In other words, when these athletes performed their respective skill in a predictable environment and without attention, they were

successful. When they paid attention to the low-level mechanics of the task, their performance declined.

According to hierarchical control theory (HCT), the aforementioned findings highlight a key difference between the outer and inner loop of control, which is the focus of the current research. The outer loop requires attention to be allocated to the task for successful performance while the inner loop suffers when attention is applied. This can be formalized with two novel premises of HCT that lead to the predictions tested in the current research. Premise 1 states that performance based on the outer loop should get better with *more* attention allocated to the task and get worse with *less* attention allocated to the task. Premise 2 states that performance based on the inner loop should get better with *less* attention allocated to the task and get worse with *more* attention allocated to the task.

Once again, typing can be used to illustrate predicted performance based on these premises. When typing with a new keyboard arrangement or in an unpredictable setting, typists will require more attention for successful performance. If distractions divert attention from the task of typing, performance will get worse. Typing in this example involves outer loop processing. Thus, diverting attention from performance based on the outer loop of control negatively impacts performance. On the other hand, when typing on a normal keyboard and in a predictable setting, experienced typists can rely on inner loop processing of the keystrokes. If distractions divert attention from the task of typing, performance will improve. Typing in this second example involves inner loop processing, which requires minimal attention. Thus, diverting attention from performance based on the inner loop of control positively impacts performance.

The typing examples above make the case that altering primary task predictability and secondary task workload can allow one to test features of HCT. It is important to note that predictions based on Premise 1 and Premise 2 have never been formally tested. Indeed, some of the most recent research on HCT has focused only on the part of Premise 2 that states that performance should be impaired when more attention is allocated to a task (Logan & Crump, 2009; Tapp & Logan, 2011; Yamaguchi, Logan, & Bissett, in press). In addition, the current research tests features of HCT in a new domain. Specifically, the current research will test predictions based on the two premises of HCT for evidence of outer and inner loop processing in the domain of driving an automobile by manipulating primary task predictability and secondary task workload.

### Driving and Driver Distraction

Driving is a complex, goal directed skill that involves a high demand on cognitive and motor processes (Groeger, 2000). Despite the demands on cognitive and motor processes, a majority of residents in the United States engage in driving on a regular basis. For example, the Federal Highway Association reports that there are over 210 million licensed drivers in the United States, which is approximately 685 drivers for every 1,000 residents. In 2009 alone, over 85% of the driving-age population had a license, and it is estimated that this trend will continue in the coming years (Our Nation's Highways, 2011). Outside of the United States, driving is also prevalent. For example, China recently reported having over 260 million registered drivers as of 2012 (<http://www.wautom.com/2013/02/260-million-drivers-registered-in-china-in-2012/>). In addition to the number of drivers, a recent report found that the world population of vehicles

has surpassed 1 billion in 2010 and is projected to exceed 2.5 billion by 2050 (Sousanis, 2011).

As the prevalence of driving continues to increase, so too has the prevalence of distracted driving. According to the National Highway Traffic Safety Administration (NHTSA), approximately 25% of all crashes are related to distracted driving, and at least one form of distracted driving involves talking on a cell phone (2009). Despite the dangers of distracted driving, more than two thirds of people surveyed reported using a cell phone while driving (AAA Foundation for Traffic Safety, 2009). Understanding the sources of distracted driving is important for improving public safety, and it is important for better understanding how a complex skill like driving is hierarchically controlled.

There are several sources of interference that contribute to driver distraction. Visual interference can arise when drivers take their eyes off the road. Manual interference can arise when drivers take their hands off the wheel. Cognitive interference can arise when drivers take their attention off important information needed for safe driving. Importantly, cognitive distraction can occur even when drivers have their eyes on the road and their hands on the steering wheel, for example, when using a hands free cell phone (Strayer, Watson, & Drews, 2011). Prior research has found that cognitively distracted drivers are more likely to miss important traffic signals, are slower to respond to signals they do detect, and are more likely to be involved in rear-end collisions (Redelmeier & Tibshirani, 1997; Strayer et al., 2003).

What is particularly interesting about cognitive distraction is that it can produce counter-intuitive patterns across the subtasks of driving. On the one hand, when drivers are distracted, response times are slower, following distances increase, and drivers are less able to detect novel or unexpected events in the driving environment (Strayer, Drews, & Crouch,

2006; Strayer & Johnston, 2001). This is to be expected if these aspects of driving require the same resources that are being consumed by a secondary task, such as a cell phone conversation (Kahneman, 1973; Norman & Bobrow, 1975). In terms of HCT, these aspects of driving would be less predictable which means they would require outer loop processing. According to Premise 1, as attention is diverted away from driving, performance based on the outer loop of control should get worse (e.g., increased brake response times, lower detections rates, etc.).

On the other hand, examinations of lane maintenance have paradoxically found improvements with cognitive distraction. That is, as cognitive workload increases, lane maintenance improves as measured by decreases in lane position variability<sup>1</sup> (Atchley & Chan, 2011; Becic et al., 2010; Beede & Kass, 2006; Brookhuis, De Vries, & De Waard, 1991; He & McCarley, 2011; Horrey & Simons, 2007; Horrey & Wickens, 2004; Jamson & Merat, 2005; Knappe et al., 2007; Liang & Lee, 2010; Östlund et al., 2004; Reimer, 2009). As people become more engaged in a cognitively demanding, secondary task, they stay in their lanes better, and as yet there has been no adequate explanation for this paradoxical finding.

One hypothesis for why lane position variability decreases as cognitive workload increases has to do with eye movements. Research has found that drivers tend to steer in the direction of visual gaze and gaze in the direction they intend to steer (Readinger et al., 2002; Rogers, Kadar, & Costall, 2005; Wilson, Chattington, & Marple-Horvat, 2008). In addition,

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<sup>1</sup> While some have argued that decreased lane position variability represents impaired lane maintenance (Mehler, Reimer, Coughlin, & Dusek, 2009), He and McCarley (2011) used cognitive distraction and steering coherence to wind to show that decreased lane position variability reflects improved lane maintenance. See He and McCarley (2011) for more details.

under cognitive workload, drivers tend to fixate more on objects immediately in front of their vehicles and less on the dashboard and mirrors (Recarte & Nunes, 2000; Tsai et al., 2007; Victor, Harbluk, & Engström, 2005). Thus, the tendency for drivers engaged in a secondary, cognitive task to fixate on objects near the center of the roadway may reduce the influence of lane position variation brought about by glances to peripheral objects. A recent investigation, however, dissociated eye movements and cognitive workload during driving and found that cognitive workload influenced lane position variability independent of eye movements (Cooper, Medeiros-Ward, & Strayer, in press). While the eye movement hypothesis does not explain these paradoxical findings on lane maintenance, research on HCT holds more promise.

Maintaining lane position is a driving skill that initially requires attention (Groeger, 2000). For example, when comparing novice and experienced drivers, research has found that novice drivers tend to have greater lane position variability compared to experienced drivers (Yang, Jaeger, & Mourant, 2006). With practice, lane maintenance becomes automated and requires fewer resources (Dingus et al., 1997; Michon, 1985). One of the reasons for this is that roadways seldom vary in sudden, unexpected ways. In terms of HCT, this suggests that experienced drivers can rely on inner loop processing for lane maintenance on predictable roadways. In addition, most vehicles do not vary greatly in terms of how they handle the road. This type of consistent mapping is ideal for skilled performance, and often experienced drivers are able to transfer from one vehicle to another with ease and little frustration. Because of these consistent mappings, lane maintenance becomes more characteristic of the inner loop of control, which is automatic and effortless. Another reason for the transition from the outer to the inner loop has to do with the invariant visual

information in the roadway. For example, it is possible that drivers can use simple calculations using two visual points (a far and a near point) to update the steering wheel angle for a desired trajectory (Land & Lee, 1994). The near point helps with lane maintenance while the far point helps with stability based on the upcoming roadway (Donges, 1978). Attributing lane maintenance to an inner loop task in predictable environments also helps to explain why experienced drivers who mind wander, or are otherwise cognitively distracted, do not drive off the road. In these instances, the inner loop of control can handle lane maintenance, and the outer loop of control is free to mind wander or perform other secondary tasks.

Because lane maintenance is an automatic skill for experienced drivers, it is an ideal measure for testing HCT. The current investigation manipulated driving predictability and secondary task workload to test predictions of HCT. These predictions stem from the aforementioned premises of HCT, and they provide evidence for outer and inner loop control. They also provide a novel framework for understanding driving and other complex skills. As it has already been mentioned, it is plausible that lane maintenance can be under the purview of the inner loop of control for experienced drivers in predictable driving conditions. In order to test the prediction based on Premise 1, one must first make lane maintenance more difficult so that it requires outer loop processing. For experienced drivers, one way to accomplish this is to make the driving environment less predictable, for example, by introducing crosswinds. Crosswinds represent an unpredictable external force pushing the vehicle out of the desired lane of travel. As a result, maintaining lane position should become more difficult and should require more attention allocated to the task. According to Premise 1, performance based on the outer loop of control should get better with more attention

allocated to the task and worse with less attention allocated to the task. If drivers engage in a secondary task while driving in windy conditions, attention would be diverted from the task of lane maintenance, and performance would suffer. In contrast, if drivers focus on the primary task of driving in windy conditions, attention would not be diverted from lane maintenance. As a result, lane maintenance should be better. Impairments in lane maintenance when going from single-task driving to dual-task driving in windy conditions would provide support for Premise 1.

In order to test the prediction based on Premise 2, driving conditions first need to be highly predictable. For experienced drivers, this could mean driving on straight roadways without crosswinds. According to Premise 2, performance based on the inner loop of control should get better with less attention allocated to the task and worse with more attention allocated to the task. Thus, if drivers engage in a secondary task without wind, the secondary task would divert attention away from lane maintenance, and performance should improve (i.e., lane position variability should decrease). Improvements in lane maintenance when going from single-task driving to dual-task driving without wind would provide support for Premise 2. Taken together, the predictions based on Premise 1 and Premise 2 are essential for testing HCT of complex skills. In addition, the prediction based on Premise 2 of HCT will help to differentiate HCT from another influential model of skilled performance referred to as ACT-R (Anderson & Lebiere, 1998; Salvucci & Beltowska, 2008).

Anderson (1996) developed his theory of ACT-R (Adaptive Control of Thought-Rational) in order to model complex human behavior. ACT-R claims that there are two different types of knowledge: declarative and procedural. Declarative knowledge consists of chunks of information that can be facts (e.g., the capital of Iowa is Des Moines), goals (e.g.,



turn left in two blocks), or other types of situational information (e.g., there is a semi in the lane next to me). Procedural knowledge consists of production rules that are used to manipulate declarative knowledge (Anderson et al., 2004). When certain conditions are met in a given environment, these production rules lead to subsequent actions that can change facts, set goals, or bring about other behaviors. ACT-R has been used in over 700 publications, and it has been used to model a wide variety of tasks from basic serial recall tasks in the laboratory (Anderson & Matessa, 1997) to more complex tasks involving air traffic control (Lee & Anderson, 2001) and fighter pilots (Jones et al., 1999). Important for the current research, ACT-R has also been used to predict both primary and secondary task performance in the domain of driving.

Salvucci (2006) adapted a version of ACT-R to predict driving behavior. He highlighted the fact that ACT-R has built in perceptual and motor modules that can work in parallel in a way that resembles complex human behavior. For example, a driver can perceive an object in the road ahead while also braking. In addition to these modules, there is a cognitive processor that receives all information from the perceptual module and is also in charge of all that goes into the motor module. While these modules can happen in parallel, the cognitive processor operates in a serial fashion. As a result, when driving becomes unpredictable, the cognitive processor must switch between the various subtasks of driving in addition to the perceptual and motor modules. For example, in driving conditions that have crosswinds, the cognitive processor would switch between monitoring the upcoming roadway, perceiving the strength and direction of the wind, and making adjustments to steering inputs. As the wind becomes stronger and less predictable, performance would

decline because the demand on the cognitive processor would increase. In terms of HCT, this is akin to performance based on the outer loop of control.

In addition to predicting performance in unpredictable driving conditions, ACT-R has been used to predict dual-task driving performance in highly predictable driving conditions. Salvucci (2006) argued that when drivers engage in secondary tasks, the cognitive processor must switch between the secondary tasks and driving, which results in suboptimal driving performance. With regard to lane maintenance, ACT-R predicts that lane maintenance should also be degraded when drivers are cognitively distracted because the cognitive processor still must switch between the cognitive tasks and lane maintenance in a serial fashion. In terms of HCT, this is in contrast to performance based on the inner loop of control (i.e., Premise 2).

### Experimental Overview

The current research consists of several experiments that tested HCT in the domain of driving using lane maintenance as the primary dependent variable. Experiment 1 manipulated primary task predictability and secondary task workload and showed that increasing cognitive distraction led to improved lane maintenance in predictable driving environments while increasing cognitive distraction led to impaired lane maintenance in less predictable driving conditions (i.e., wind). Experiment 2 replicated these results with calibrated primary task predictability and secondary task workload using information theory. The results from Experiments 1 and 2 provide evidence for both outer and inner loop processing, and they suggest that the involvement of these loops depends on the predictability of the driving environment, as well as the presence or absence of secondary, cognitive tasks. Specifically, in less predictable driving environments (i.e., windy conditions), the task of lane maintenance

requires the outer loop of control. When a secondary, cognitive task is added, attention is diverted away from lane maintenance, leading to *impaired* lane maintenance. This follows from Premise 1 because performance based on the outer loop of control should get better with more attention allocated to the task and get worse with less attention allocated to the task.

In highly predictable driving environments (i.e., without wind), the inner loop of control is sufficient for lane maintenance. When a secondary, cognitive task is added, attention is diverted away from lane maintenance, leading to *improved* lane maintenance. This follows from Premise 2 because performance based on the inner loop of control should get worse with more attention allocated to the task and get better with less attention allocated to the task. It is important to note that these premises and their subsequent predictions provide a novel framework for testing HCT that goes beyond previous research on hierarchical control. Furthermore, Premise 2 will test between theoretical predictions of HCT and ACT-R. By dissociating the hierarchical control loops in the domain of driving, the current research will account for previous driving research while also providing a novel framework for testing features of HCT with other complex skills.

## EXPERIMENT 1

Experiment 1 was designed to test HCT using a driving simulator. Specifically, Experiment 1 manipulated primary task predictability and secondary task workload to dissociate the outer and inner hierarchical control loops. It was predicted that as driving became less predictable due to crosswinds, the outer loop of control would be required for performance. Subsequently, if secondary, cognitive tasks were added, attention would be diverted from the task of lane maintenance thereby impairing lane maintenance (i.e., increased lane position variability). In contrast, it was predicted that in highly predictable driving conditions (i.e., without wind), the inner loop of control would be sufficient for performance. Subsequently, if secondary, cognitive tasks were added, attention would be diverted from the task of lane maintenance. Rather than impairing performance, this would lead to improvements in lane maintenance (i.e., decreased lane position variability).

### Methods

#### *Participants*

Twenty-four participants (12 male and 12 female) with normal or corrected-to-normal vision and valid driver's licenses were recruited from the University of Utah psychology undergraduate participant pool. Participants were between 19 and 34 years old (mean age = 25), were fluent in English, and reported having their normal amount of sleep and caffeine

prior to the study. Participants were compensated with credit towards a psychology course requirement.

### *Materials*

Driving performance data were collected using a high-fidelity, fixed-base driving simulator. The simulator recreated a realistic driving environment through the use of dashboard instrumentation, steering wheel, and gas and brake pedals taken from a typical sedan with an automatic transmission. The roadway was a straight three-lane highway, and speed was held constant at 68 mph simulated using cruise control to reduce any effects from speed fluctuations and to provide greater experimental control (Cooper et al., in press; Medeiros-Ward et al., 2010). Measurements of lane position variability were collected for later analysis.

### *Design*

The design was a 2 (cognitive workload) X 2 (wind) factorial which was counterbalanced across participants using a balanced Latin Square. A within subjects design was used to measure lane position variability. There were two levels of cognitive workload: Single-task driving and counting backward by 3. This secondary task has been used in studies on information reduction (Pellecchia & Shockley, 2005). Information reduction allows one to vary the attentional requirements of activities by altering the processing demands of the tasks involved (Cooper et al., in press; Posner, 1964; Posner & Rossman, 1965). There was a 5.9 bit reduction for the counting backward by 3 task.

There were also two levels of wind: No wind and high wind. The lateral wind was created by the sum of three sine waves representing gusts each with amplitudes of 25 mph (plus a 40 mph constant wind) but different frequencies (.077 Hz, .059 Hz, and .032 Hz). Prior research has found these algorithms to produce realistic crosswinds similar to those encountered on a multilane highway (Anderson & Ni, 2005; He & McCarley, 2011).

### *Procedure*

Informed consent was obtained at the beginning of the session. Following consent, participants completed a warm-up scenario to allow for adaptation to the driving simulator. Following the warm-up scenario, participants were trained on the counting backward task before completing the four driving scenarios in one experimental session lasting approximately 30 minutes. In all scenarios, participants were instructed to drive in the middle lane of a three-lane highway with their hands on the wheel at all times. They were told that a cruise control had been set so they would only need to worry about steering. For the counting backward task, participants counted backward out loud by threes from a randomly selected three-digit number between 100 and 999. Similar to previous research, participants did not receive feedback about their performance during the experiment but were instructed to respond as quickly and accurately as possible (Pellecchia & Shockley, 2005).

### Results

The means and standard errors for the standard deviation of lane position are presented in Table 1. The standard deviation of lane position was analyzed using a 2 X 2 repeated measures Analysis of Variance (ANOVA). There was a marginally significant effect

of cognitive workload ( $F(1,23) = 3.59, p = .07$ , partial  $\eta^2 = .14$ ). There was also a significant effect of wind ( $F(1,23) = 101.90, p < .05$ , partial  $\eta^2 = .82$ ). Most importantly, there was a significant interaction between cognitive workload and wind ( $F(1,23) = 25.95, p < .05$ , partial  $\eta^2 = .53$ ). As cognitive workload increased without wind, lane position variability decreased. When wind was added, lane position variability increased (Figure 1). Planned pairwise comparisons indicated that without any wind, there was a significant *decrease* from the single-task condition to the dual-task condition; however, with wind, there was a significant *increase* from the single-task condition to the dual-task condition.

### Discussion

Experiment 1 manipulated primary task predictability and secondary task workload as drivers maintained lane position. The effects of these manipulations differed depending on which hierarchical control loop was required for performance. When the primary task of driving was less predictable due to crosswinds, the outer loop of control should have been required for performance. According to Premise 1 of HCT, performance based on the outer loop of control should get better with more attention allocated to the task and worse with less attention allocated to the task. Thus, when a secondary, cognitive task was added, attention should have been diverted from the task of lane maintenance, and performance should have been impaired (i.e., increased lane position variability). The results of Experiment 1 supported this prediction.

When the primary task of driving was highly predictable (i.e., without wind), the inner loop of control should have been sufficient for performance. According to Premise 2 of HCT, performance based on the inner loop of control should get worse with more attention

allocated to the task and better with less attention allocated to the task. Thus, when a secondary, cognitive task was added, attention should have been diverted from the task of lane maintenance similar to performance based on the outer loop. Rather than impairing performance, diverting attention away from the task of lane maintenance should have improved performance (i.e., decreased lane position variability). The results from Experiment 1 supported this prediction as well.

Experiment 1 found support for the predictions based on Premise 1 and Premise 2 of HCT, which suggests that a complex skill, such as lane maintenance, is organized hierarchically. Furthermore, these results suggest that the level of control required for performance on the very same task ultimately depends on the predictability of the environment and the presence or absence of a secondary, cognitive task. In other words, lane maintenance can be controlled by either the outer or the inner loop depending on driving task predictability. Experiment 2 was designed to replicate these effects and to calibrate the levels of primary task predictability and secondary task workload using information theory.



Table 1

Experiment 1: Means and Standard Errors for the Standard Deviation of Lane Position

Workload	Predictability	Mean	SE
Single task	No wind	.221	.012
	High wind	.287	.013
Dual task	No wind	.168	.011
	High wind	.311	.014

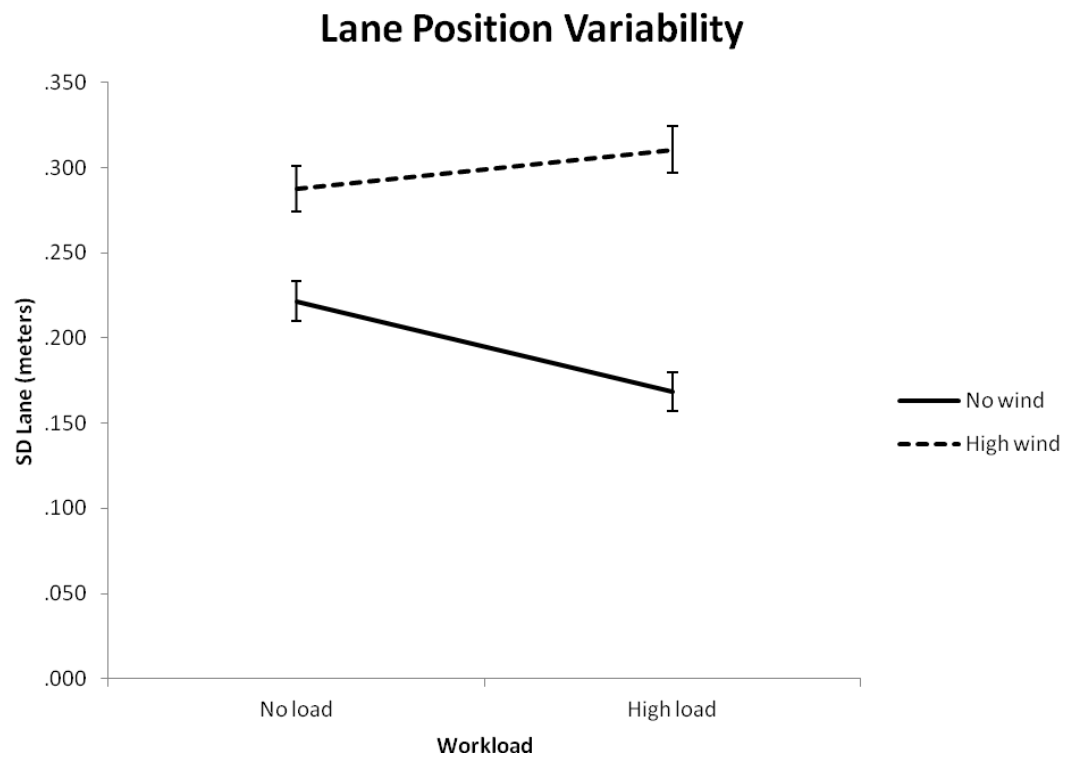


Figure 1

#### Experiment 1

Interaction between cognitive workload and wind on lane position variability (error bars indicate standard errors of the mean).

## EXPERIMENT 2

Given the novel results from Experiment 1, the first goal of Experiment 2 was to replicate and extend the findings from Experiment 1. This is especially important given the recent emphasis on replication and reproducibility in the field of psychological science (Pashler & Wagenmakers, 2012). By replicating Experiment 1, Experiment 2 ensured that the findings in Experiment 1 are reliable and that the case for HCT is robust.

In addition to replicating Experiment 1, Experiment 2 calibrated the levels of primary task predictability and secondary task workload using information theory. For secondary task workload, Experiment 1 used an information reduction task similar to previous research; however, accuracy was not recorded nor was the presentation of stimuli kept constant. Thus, Experiment 2 used a more controlled task to systematically increase cognitive demand while holding all other parameters constant. The levels of cognitive workload came from a delayed digit recall n-back task developed by the MIT AgeLab (Mehler, Reimer, & Dusek, 2011). This task was designed to systematically increase the cognitive demand on participants, and it has been used in several distracted driving studies (Mehler, Reimer, & Coughlin, 2012; Reimer & Mehler, 2011; Reimer, Mehler, Wang, & Coughlin, 2012). In Experiment 2, the three levels of cognitive workload were single-task, 0-back, and 2-back. In the single-task condition, participants simply drove without a secondary cognitive task. In the 0-back and 2-back conditions, participants were presented with auditory lists of numbers ranging from 0 to 9 in four sets of 10 randomized sequences. For the 0-back condition, participants were

instructed to say out loud the number they had just heard. For the 2-back condition, participants were instructed to say out loud the number two times before the number they had just heard. For all conditions, participants were instructed to respond as accurately as possible. Responses were recorded for later analysis.

In addition to refining the secondary task workload, Experiment 2 used entropy measures from information theory to calibrate the level of unpredictability associated with the levels of wind. Entropy is a measure of uncertainty associated from a random variable. In a driving context, as one encounters lateral wind on a highway, one must allocate more attention to lane position maintenance in order to counteract the force of the wind and stay in the lane. As the wind becomes more unpredictable, staying in the lane becomes increasingly more difficult, and more attention is allocated to the task of lane maintenance. In other words, the entropy or uncertainty of the task increases (Shannon, 1948). Specific to this research, entropy served as a way to calculate the uncertainty associated with various levels of wind in the simulator. In Experiment 2, three levels of wind entropy were created using entropy estimates from information theory. The levels were low entropy, medium entropy, and high entropy. In the low entropy condition there was no wind. In the medium entropy condition, there was a constant lateral wind (40 mph) and a single gust (25 mph and .077 Hz). In the high entropy condition, there was a constant lateral wind (40 mph) and three gusts (all at 25 mph and .077 Hz / .059 Hz / .032 Hz). These levels of entropy created a steady increase of uncertainty for participants trying to maintain a central lane position, which was calculated using basic Shannon entropy measures (Coifman & Wickerhauser, 1992; Donoho & Johnstone, 1994). Specifically, there were 5.91 bits of entropy in the medium entropy condition and 23.61 bits in the high entropy condition.

## Methods

### *Participants*

Twenty-seven participants (11 male and 16 female) with normal or corrected-to-normal vision and valid driver's licenses were recruited from the University of Utah psychology undergraduate participant pool. Previous research using a similar design found this to be an appropriate number of participants to detect any purported effects (Cooper, Medeiros-Ward, & Strayer, in press). They were between 19 and 43 years old (mean age = 25) and were fluent in English. Participants had their normal amount of sleep and caffeine prior to the study.

### *Materials and Design*

The driving simulator and data analysis tools in Experiment 2 were identical to those in Experiment 1. A within subjects design was used to measure lane position variability across nine different driving scenarios. The order of these scenarios was counterbalanced across participants using a balanced Latin Square.

### *Procedure*

Informed consent was obtained at the beginning of the session. Following consent, participants completed a warm-up scenario to allow for adaptation to the driving simulator. In addition to the driving warm-up, participants completed a standardized training protocol on the delayed digit recall n-back task until they achieved at least 85% accuracy on all levels. Following the secondary task training, participants completed nine driving scenarios in one experimental session lasting approximately 90 minutes. In all scenarios, participants were

instructed to drive in the middle lane of a three-lane highway with their hands on the wheel at all times. They were told that a cruise control had been set so they only needed to worry about steering.

### Results

The means and standard errors for the standard deviation of lane position are presented in Table 2. The standard deviation of lane position was analyzed using a 3 X 3 repeated measures ANOVA. There was no effect of cognitive workload ( $F(2,52) = 0.44, p = ns$ ). There was a significant effect of wind entropy ( $F(2,52) = 69.47, p < .05$ , partial  $\eta^2 = .73$ ). Most importantly, there was a significant interaction between workload and wind entropy ( $F(4,104) = 24.28, p < .05$ , partial  $\eta^2 = .48$ ). Pairwise comparisons indicated that as cognitive workload increased without wind, lane position variability decreased. When both cognitive workload and wind entropy increased, lane position variability increased in a way that was similar to Experiment 1 (Figure 2). In the low entropy condition, lane position variability decreased from the single-task condition to the 0-back condition and finally to the 2-back condition. In the medium entropy condition, the effects of primary task predictability and secondary task workload canceled each other out. Finally, in the high entropy condition, lane position variability increased from the single-task condition to the 0-back condition and finally to the 2-back condition, which had the highest lane position variability out of all nine conditions. For both the low entropy condition and high entropy condition, all of the levels of cognitive workload significantly differed from each other ( $p < .05$ ).

Performance on the secondary, cognitive task was analyzed using a one way repeated measures ANOVA. There was an effect of load ( $F(1,26) = 23.74, p < .05$ , partial  $\eta^2 = .48$ ).

Pairwise comparisons indicated that participants were nearly perfect on the 0-back task ( $M = 1.0$ ,  $SE = .00$ ) but less accurate on the 2-back task ( $M = .86$ ,  $SE = .03$ ). These levels of accuracy are nearly identical to those found in other distracted driving studies that used the same secondary, cognitive task (Mehler et al., 2012).

Table 2

Experiment 2: Means and Standard Errors for the Standard Deviation of Lane Position

Workload	Predictability	Mean	SE
Single task	Low entropy	.231	.011
	Medium entropy	.244	.010
	High entropy	.260	.009
0-back	Low entropy	.198	.008
	Medium entropy	.261	.012
	High entropy	.279	.008
2-back	Low entropy	.176	.008
	Medium entropy	.254	.010
	High entropy	.309	.011



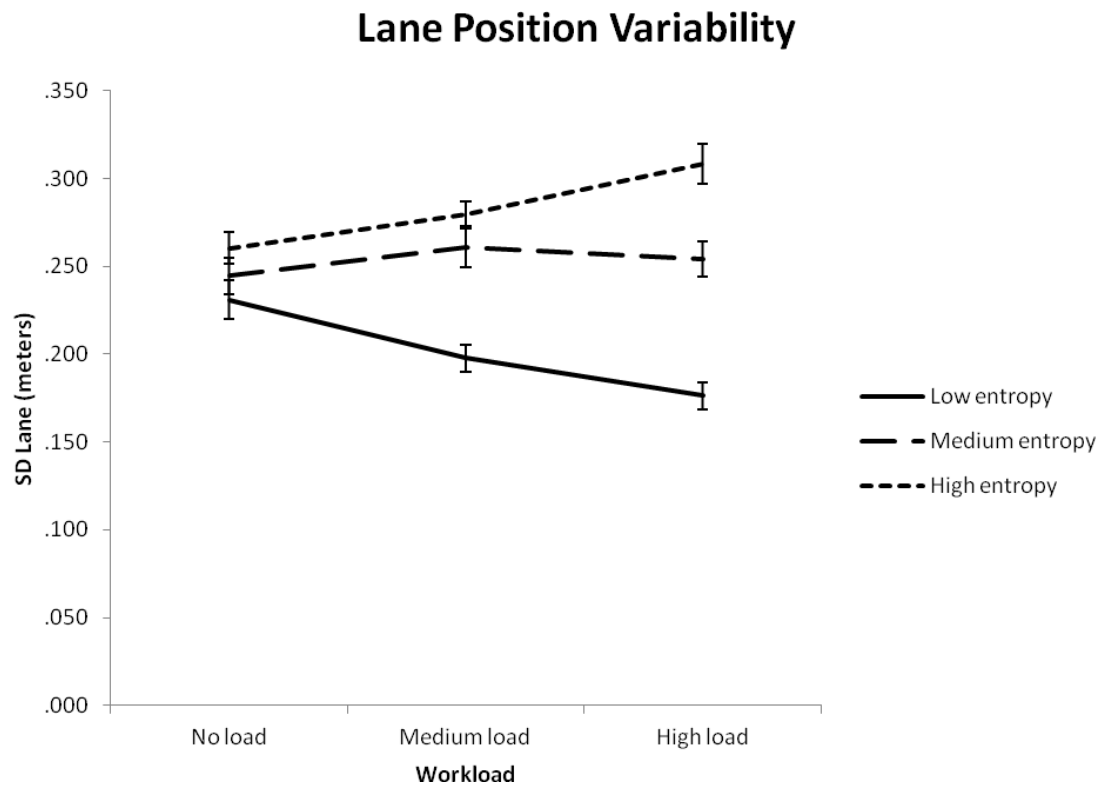


Figure 2

## Experiment 2

Interaction between cognitive workload and wind entropy on lane position variability (error bars indicate standard errors of the mean).

## GENERAL DISCUSSION

Complex skills are an important part of human life. According to HCT, complex skills are organized hierarchically with performance sometimes depending on an outer loop of control while other times depending on an inner loop of control. Which loop is involved in performance depends on the properties of each loop, as well as the task predictability and available attention. These hierarchical control loops have distinct properties. For example, the outer loop of control is more effortful and requires attention for successful performance while the inner control loop is more effortless and requires minimal attention for successful performance. This difference led to several predictions based on two novel premises of HCT that were tested in the current research. Premise 1 claims that performance based on the outer loop of control should get better with more attention allocated to the task and worse with less attention allocated to the task. Premise 2 claims that performance based on the inner loop of control should get worse with more attention allocated to the task and better with less attention allocated to the task. Given these properties, Experiments 1 and 2 were designed to dissociate these hierarchical control loops in the domain of driving by manipulating primary task predictability and secondary task workload. Specifically, when a secondary, cognitive task was added to an unpredictable driving environment (i.e., with wind), lane maintenance was impaired. This is expected given that the outer loop would most likely be responsible for performance in unpredictable settings. A secondary, cognitive task would divert attention away from lane maintenance leading to impairments in lane maintenance. When a secondary,

cognitive task was added to a highly predictable driving environment (i.e., no wind), lane maintenance improved. This is expected given that the inner loop is sufficient for performance in highly predictable settings. A secondary, cognitive task would divert attention away from lane maintenance, but rather than leading to impairment, this diversion would lead to improvements given the properties of the inner loop of control.

Experiment 2 replicated Experiment 1, which established that the effects in Experiment 1 are robust and reliable. In addition, Experiment 2 refined the levels of primary task predictability and secondary task workload using information theory. By doing so, Experiment 2 created theoretically-justified manipulations of wind and cognitive workload. Both Experiments 1 and 2 provide strong support for the predictions based on Premise 1 and Premise 2. Overall this research provides a framework for testing HCT on a variety of complex skills.

The novel premises of HCT are also important because together they predict performance in a way that is inconsistent with the ACT-R model of skilled performance. Specifically, in terms of Premise 2, performance based on the inner loop should get worse with more attention and better with less attention. Thus, when drivers engage in secondary tasks, lane maintenance should improve because attention is being diverted away from lane maintenance. Indeed, this prediction was supported in both Experiment 1 and Experiment 2. In contrast, ACT-R predicts that as cognitive workload increases, lane maintenance should get worse. This is because cognitive workload requires the same processing resources that are important for maintaining lane position (Salvucci, 2002).

Interestingly, Salvucci and Beltowska (2008) found that lane maintenance got worse as cognitive workload increased. This is in contrast to research that has found improvements

in lane maintenance with increased cognitive workload (Atchley & Chan, 2011; Becic et al., 2010; Beede & Kass, 2006; Brookhuis, De Vries, & De Waard, 1991; He & McCarley, 2011; Horrey & Simons, 2007; Horrey & Wickens, 2004; Jamson & Merat, 2005; Knappe et al., 2007; Liang & Lee, 2010; Östlund et al., 2004; Reimer, 2009). In their study, Salvucci and Beltowska (2008) placed construction cones on both sides of the road so that drivers would maintain a central lane position. It is possible that the construction cones increased the level of difficulty in the driving scenario. As a result, it is possible that their driving task reflected outer loop performance, and they did not fully capture inner loop performance. If so, this would explain why their results differed from a growing body of research on cognitive distraction and decreases in lane maintenance.

In addition to distinguishing HCT from ACT-R, the current research can help to explain several intriguing aspects of driving. Many drivers who are distracted or mind wandering arrive at their destinations without driving off the road. Previously, there was no satisfactory explanation for how this could happen. If one adopts a theory similar to ACT-R, then one might expect lane maintenance to get worse with less attention regardless of the primary task predictability. By adopting HCT, we can now understand why distracted drivers do not drive off the road. Importantly, this does not mean that distraction leads to improvements on other measures of driving. For example, if distracted drivers are required to respond to novel information (e.g., a pedestrian stepping out into the road from behind a parked car or a suddenly braking lead vehicle), they are less likely to respond quickly and accurately (Redelmeier & Tibshirani, 1997; Strayer et al., 2003). This would rely on the outer loop of control, and performance based on the outer loop of control gets worse with less

attention. When drivers engage in secondary tasks, their attention is diverted from the task of detecting novel stimuli in the environment.

Future studies could vary the predictability of novel stimuli so that in some cases their appearance would be very periodic and predictable while in other cases their appearance would be aperiodic and less predictable. Similar to the current research, as novel stimuli become more and more predictable, less attention would be needed for successful performance. Of course, it is hard to imagine a situation outside of the laboratory in which the predictability of novel stimuli could be controlled entirely.

One final note can be made about the hierarchical control model used in the current proposal. There are, in fact, several different theories of hierarchical control used to model driving behavior. One of the most well-known is Michon's (1985) hierarchy of skills and control. According to Michon (1985), there is an operational level, a tactical level, and a strategic level of control. In terms of driving, the operational or control level involves handling control inputs needed for stable driving performance. The tactical or maneuvering level involves the safe interactions with other cars and the environment in general. Finally, the strategic or planning level involves higher level planning or reasoning (e.g., deciding which route to take home from the airport). Hierarchical models like Michon's are typically engineer-focused and do not adequately consider human cognition as an essential part of the model. In addition, they tend to be process models that consider tasks to be specific to a designated level. For example, Michon (1985) claims that lane maintenance is an operational or control level task. In contrast, the current research has shown that lane maintenance can be an outer or an inner loop task depending on driving predictability and secondary task

workload. We suggest that HCT provides a generalized framework for understanding complex skills including driving.

## APPENDIX A

### EXPERIMENT 1A

While Experiment 1 found preliminary support for a hierarchical control model of driving, it was not clear whether or not the effect could be manipulated using more refined levels of cognitive workload and wind. Thus, Experiments 1a and 1b helped to calibrate each independent variable in a theoretically meaningful manner. For Experiment 1a, a within subjects design was used to measure lane position variability across six different levels of cognitive workload. Based on HCT, as cognitive workload increased, the outer loop was required to complete the secondary tasks. This allowed the inner loop to control lane position maintenance without disruption from the outer loop. Importantly, the levels of the cognitive workload were established in a theoretically-driven manner to determine how cognitive distraction related to lane position variability.

For Experiment 1a, five levels of cognitive workload (in addition to a single task scenario) were established using information reduction (Pellecchia, 2003; Posner, 1966). Information reduction allows one to vary the attentional requirements of activities by altering the processing demands of the tasks involved (Posner, 1964; Posner & Rossman, 1965). One can calculate the amount of information reduction, which becomes a proxy for attentional demand, by quantifying the number of information bits in the input and output for a given task, and the difference between the input and output represents the amount of information

reduced (Pellecchia & Turvey, 2001). The levels of cognitive workload used for Experiment 1a included a digit reversal task (0 bit reduction), a digit addition task (2.7 bit reduction), a digit classification task (4.5 bit reduction), a counting backward by 3 task (5.9 bit reduction), and a counting backward by 7 task (7.6 bit reduction). These tasks are described in more detail below.

## Methods

### *Participants*

Thirty participants with normal or corrected-to-normal vision and valid driver's licenses were recruited from the University of Utah psychology undergraduate participant pool. They were between 18 and 27 years old (12 male and 18 female) and were fluent in English. Participants were also free from any neurological disorders and reported having their normal amount of sleep and caffeine prior to the study. Participants were compensated with credit towards a psychology course requirement.

### *Materials and Design*

The driving simulator and data analysis tools in Experiment 1a were identical to those in Experiment 1. A within subjects design was used to measure lane position variability across the six levels of cognitive workload. The order of these scenarios was counterbalanced across participants using a balanced Latin Square.



### *Procedure*

Informed consent was obtained at the beginning of the session. Following consent, all participants completed a basic demographic survey and a warm-up scenario. Following the warm-up scenario, participants completed the six driving scenarios in one experimental session lasting approximately 45 minutes. In all scenarios, participants were instructed to drive in the middle lane of a three-lane highway with their hands on the wheel at all times. They were told that a cruise control had been set so they only needed to worry about steering. For the digit reversal task, participants reported two digits in the order opposite from their presentation. For example, if participants heard “2...7”, they would report “7...2”. For the digit addition task, participants reported the sum of two randomly selected digits. For example, if participants heard “2...7”, they would report “9”. For the digit classification task, participants classified a pair of digits as high ( $>50$ ) or low ( $<50$ ) and odd or even. For example, if participants heard “2...7”, they would report “odd...high”. For the counting backward by 3 task, participants counted backward by threes from a randomly selected three-digit number between 100 and 999. Finally, for the counting backward by 7 task, participants counted backward by 7s from a randomly selected three-digit number between 100 and 999. For all of these tasks, responses were recorded by the experimenter and used to calculate accuracy. Similar to previous research, participants did not receive feedback about their performance during the experiment but were instead told to do their best to respond quickly and accurately (Pellecchia & Shockley, 2005).

## Results

The standard deviation of lane position was analyzed for each participant in each condition using a one way repeated measures ANOVA. There was a significant main effect of cognitive workload on lane position variability ( $F(5,145) = 13.51, p < .05$ , partial  $\eta^2 = .32$ ). Pairwise comparisons indicated that as cognitive workload increased, lane position variability decreased.

## Discussion

The goal of Experiment 1a was to calibrate the levels of cognitive workload in a way that was theoretically meaningful. It was predicted that as cognitive workload increased, the outer loop of control would be increasingly engaged in the secondary tasks, which would allow the inner loop to control performance without disruption from the outer loop. As a result, lane position maintenance improved (i.e., lane position variability decreased). The significant main effect supports the fact that participants were not able to allocate as much attention to lane position as workload increased because they were engaged in the secondary tasks. Single task driving led to greater lane position variability than each of the other tasks. Interestingly, while information reduction theory predicted significant differences in the attentional demand across the levels of workload, the only marginally significant difference was between the digit reversal task and the counting backward by 3 task ( $p = .07$ ). Nonetheless, this established theoretically informed manipulations of cognitive workload that can be used in future studies, and it provided additional evidence that withdrawing attention from an automatic task can improve performance.

## APPENDIX B

### EXPERIMENT 1B

The goal of Experiment 1b was to calibrate the levels of uncertainty caused by crosswinds in a theoretically meaningful manner. Unlike Experiment 1a, which used very predictable driving scenarios to test the effects of several different levels of cognitive distraction, Experiment 1b held the level of cognitive distraction constant while varying the levels of crosswinds. When there are no crosswinds, the driving environment is fairly predictable, especially the roadway, which allows the inner loop to maintain lane position with minimal interference from attention. When crosswinds are introduced, however, the driving environment becomes less predictable. Specifically, drivers now have an external force acting upon their cars in a random fashion. These crosswinds push drivers out of their lanes, and in order for drivers to counteract the wind, the outer loop must be engaged (i.e., the task is effortful rather than automatic). In other words, lane position maintenance becomes more like a novel task and requires the outer loop for successful performance.

Experiment 1b was designed to systematically vary levels of wind according to a priori levels of uncertainty while measuring lane position variability. Rather than relying on information reduction as in Experiment 1a, the various levels of wind in Experiment 1b were established using entropy measures from information theory. Entropy is a measure of uncertainty associated from a random variable. In a driving context, as one encounters lateral

wind on a highway, one must allocate more attention to lane position maintenance in order to counteract the force of the wind and stay in the lane. As the wind becomes more unpredictable, staying in the lane becomes increasingly more difficult, and more attention is directed toward the task. In other words, the entropy or uncertainty of the task increases (Shannon, 1948). Specific to this research, entropy served as a way to calculate the uncertainty associated with various wind gusts in the simulator. In Experiment 1b, four levels of lateral wind were chosen based on previous research as well as theoretically meaningful calculations from information entropy: single task (i.e., no wind), 1 gust (45 mph and .032 Hz), 2 gusts (both at 45 mph and .032 Hz / .059 Hz), and 3 gusts (all at 45 mph and .032 Hz / .059 Hz / .077 Hz). These various levels of wind created a steady increase of uncertainty for participants trying to maintain a central lane position, which was calculated using basic Shannon entropy measures (Coifman & Wickerhauser, 1992; Donoho & Johnstone, 1994). Specifically, there is no entropy in the single task condition, 5.91 bits of entropy with 1 gust, 15.09 bits with 2 gusts, and 23.61 bits with 3 gusts.

## Methods

### *Participants*

Thirty-six participants with normal or corrected-to-normal vision and valid driver's licenses were recruited from the University of Utah psychology undergraduate participant pool. They were between 18 and 38 years old (14 male and 22 female) and were fluent in English. Participants were also free from any neurological disorders and reported having their normal amount of sleep and caffeine prior to the study. Participants were compensated with credit towards a psychology course requirement.

### *Materials and Design*

The driving simulator and data analysis tools in Experiment 1b were identical to those in Experiment 1a. A within subjects design was used to measure lane position variability across the four levels of wind. The order of these scenarios was counterbalanced across participants using a balanced Latin Square.

### *Procedure*

Informed consent was obtained at the beginning of the session. Following consent, all participants completed a basic demographic survey and a warm-up scenario. Following the warm-up scenario, participants completed the four driving scenarios in one experimental session lasting approximately 30 minutes. In all scenarios, participants were instructed to drive in the middle lane of a three-lane highway with their hands on the wheel at all times. They were told that a cruise control had been set so they only needed to worry about steering. For the three scenarios with wind, participants were also told that they might encounter crosswinds but that they should try to drive in the middle lane despite any wind.

### Results

The standard deviation of lane position was analyzed for each participant in each condition using a one way repeated measures ANOVA. There was a significant main effect of wind on lane position variability ( $F(3,105) = 54.48, p < .05$ , partial  $\eta^2 = .61$ ). Pairwise comparisons indicated that as wind increased, lane position variability also increased, though this difference was only marginally significant between the single task condition and the 1 gust condition ( $p = .05$ ).

### Discussion

The goal of Experiment 1b was to calibrate the levels wind to establish theoretically meaningful manipulations of uncertainty in the driving environment and to determine how these related to lane position variability. It was predicted that a small amount of wind would make driving slightly less predictable (i.e., slightly higher uncertainty) compared to a scenario with no wind. In addition, it was predicted that greater increases in wind (i.e., 2 and 3 gusts) would lead to even higher levels of uncertainty and would require even more of the outer loop for successful performance. When a small amount of wind was applied to the driving scenario, the driving environment became less predictable as drivers tried to counteract the effects of the lateral winds. As a result, lane position maintenance became more difficult to accomplish on autopilot, and the outer loop became engaged in order to stay in the lane. Because attention was being allocated to maintaining lane position, performance declined (i.e., lane position variability). Only the differences between no wind, 2 gusts, and 3 gusts were significant despite the fact that all of the levels were established using a priori measures of entropy. Nonetheless, Experiment 1b successfully calibrated the levels of wind in a way that was theoretically meaningful for future studies.

## APPENDIX C

### EXPERIMENT 1C

While Experiment 1 found preliminary support for a hierarchical control model of driving, it was not clear whether or not the effect could be manipulated using a different secondary cognitive task that was more ubiquitous and more controlled. For example, the cognitive workload measures in Experiment 1 and Experiment 1a are limited in that the presentation of the stimuli varied across participants. Furthermore, for the counting backward by 3 task, participants set their own pace since they did not rely on an experimenter to present them with digits. As a result, it is not clear how performance might be influenced when controlling for the speed of presentation and while also taking into account accuracy. Thus, Experiment 1c helped to calibrate a different secondary cognitive task. For Experiment 1c, a within subjects design was used to measure lane position variability across four different levels of cognitive workload. Based on HCT, as cognitive workload increased, the outer loop was required to complete the secondary tasks. This allowed the inner loop to control lane position maintenance without disruption from the outer loop. Importantly, the levels of the cognitive workload were based on prior research using a delayed digit recall n-back task.

The delayed digit recall n-back task was developed by the MIT AgeLab (<http://agelab.mit.edu/delayed-digit-recall-n-back-task>). In this task, auditory stimuli are

presented at a fixed rate of 2.5 seconds. The stimuli consist of digits (from 0 to 9) and are presented in sequences of 10 digits randomly ordered across four sets. Experiment 1c tested three levels of this task in addition to a single task using lane position variability. The three levels were a 0-back, a 1-back, and a 2-back. For the 0-back condition, participants were instructed to repeat the last number they heard out loud. For the 1-back condition, participants were instructed to repeat the number before the last number they heard out loud. For the 2-back condition, participants were instructed to repeat the number two times before the last number they heard out loud. These levels have been successfully used in recent laboratory and driving research (Mehler, Reimer, & Coughlin, 2012; Reimer & Mehler, 2011; Reimer, Mehler, Wang, & Coughlin, 2012). For all levels, participants were told to respond as accurately as possible, and responses were recorded and later analyzed for accuracy.

## Methods

### *Participants*

Sixteen participants with normal or corrected-to-normal vision and valid driver's licenses were recruited from the University of Utah psychology undergraduate participant pool. They were between 19 and 33 years old (6 male and 10 female) and were fluent in English. Participants were also free from any neurological disorders and reported having their normal amount of sleep and caffeine prior to the study. Participants were compensated with credit towards a psychology course requirement.



### *Materials and Design*

The driving simulator and data analysis tools in Experiment 1c were identical to those in Experiments 1a and 1b. A within subjects design was used to measure lane position variability across the four levels of cognitive workload. The order of these scenarios was counterbalanced across participants using a balanced Latin Square.

### *Procedure*

Informed consent was obtained at the beginning of the session. Following consent, all participants completed a basic demographic survey and a warm-up scenario. In addition, participants practiced all levels of the delayed digit recall n-back task until they achieved at least 85% accuracy. Following the warm-up scenario, participants completed the four driving scenarios in one experimental session lasting approximately 30 minutes. In all scenarios, participants were instructed to drive in the middle lane of a three-lane highway with their hands on the wheel at all times. They were told that a cruise control had been set so they only needed to worry about steering.

### Results

The standard deviation of lane position was analyzed for each participant in each condition using a one way repeated measures ANOVA. There was a significant main effect of cognitive workload on lane position variability ( $F(3,45) = 23.34, p < .05$ , partial  $\eta^2 = .61$ ). Pairwise comparisons indicated that as cognitive workload increased, lane position variability decreased. The single task, 0-back, and 2-back conditions were all significantly

different from each other; however, the 1-back condition only differed from the single task condition.

Accuracy was also analyzed for each participant in each condition using a one way repeated measures ANOVA. There was a significant main effect of cognitive workload on accuracy ( $F(2,30) = 10.52, p < .05$ , partial  $\eta^2 = .41$ ). Pairwise comparisons indicated that all three levels differed from each other, and participants were most accurate in the 0-back condition ( $M = 1.00, SE = .00$ ) followed by the 1-back condition ( $M = .97, SE = .01$ ) and the 2-back condition ( $M = .90, SE = .03$ ).

### Discussion

The goal of Experiment 1c was to calibrate the levels of cognitive workload using the delayed digit recall n-back task. It was predicted that as cognitive workload increased, the outer loop of control would be increasingly engaged in the secondary tasks, which would allow the inner loop to control performance without disruption from the outer loop. As a result, lane position maintenance improved (i.e., lane position variability decreased). The significant main effect for lane position variability supports the fact that participants were not able to allocate as much attention to lane position as workload increased because they were engaged in the secondary tasks. Single task driving led to greater lane position variability than each of the other tasks. This was followed by the 0-back and then the 2-back conditions. Interestingly, the 1-back condition only differed from the single task condition and was subsequently dropped for Experiment 2. Experiment 1c established manipulations of cognitive workload that can be used in future studies, and it provided additional evidence that withdrawing attention from an automatic task can improve performance.

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